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Description

Method and Circuit Arrangement for Non-destructive Examination
10   of Objects by Means of Ultrasonic Waves

The invention relates to a method for processing signals
according to the features of the preamble of claim 1 and to a
15   circuit arrangement having the features of the preamble of
claim 16.

A method for processing signals which correspond to reflected
waves which are transmitted or interrupted by a structure in
20   order to be able to gather information and analyze the
structure of this material is described in EP 0 825 453 B1.
With the method described, the fact that every point of an
object to be examined leads to a reflected wave which is then
stored at positions of the storage unit which are distributed
25   in the form of parabolic curves, the characteristics of which
depend on the distance of the point relative to the probe and
on the radiation pattern of each element. In the known method,
a probe is used which is configured linearly and composed of a
plurality of transmitter/receiver elements of small dimensions.
30   The same probe is then used for transmission and reception.
First, a wave front is transmitted into the object to be
examined and those waves which are reflected by the structure
are received.

35   The information which is emitted by the sensor elements is then
digitalized and stored and, more particularly, is stored in a
storage element which has a line for each sensor element.

5   Subsequently, the structure of the object is reconstructed
       and/or analyzed with reference to the information that was
       stored in the storage elements. For each point of the object
       the position of the storage element is computed which contains
10   the signals which are located by the sensor elements and
       correspond to the waves reflected or transmitted from this
       point. This position is computed with aid of an addressing rule
       whose parameters depend on the position of this point in
       relation to the sensor elements. Furthermore, the lines of the
15   field storage are read for each point at the respective
       positions which were previously computed for this point, a
       mathematical operation being used for the values read for this
       point in order to obtain a result which is representative for
       the range of the wave. For the computation, all cells of the
20   storage field are read in parallel for this point at the
       positions which are designated for this point in the respective
       allocated addressed storage units.

       Since the computation of each reading principle for reading out
25   the storage would take too long to effect in real time, this
       computation is done in advance and the results stored in
       specific "address storage units" which are allocated to each
       line of the "field storage unit".

30   Hence, it follows that the described method is only suitable
       for identifying specific, i.e. previously defined structures.
       After performing the mathematical operation, the. contents of
       the field storage unit are stored in image storage unit,
       location and propagation time information being taken into
35   consideration. In the method, computed B images are evaluated,
       as is common, for example, in medical diagnostics. However,
       for automatic material examination, B images should not be

5   referred to since long evaluation times are required for the
     evaluation.

     Furthermore, it should be noted that there are limits in defect
     detection with vertical acoustic irradiation since only one
10   defective position can be detected. Furthermore, uncertainties
     occur in the defect evaluation, since fixed geometric relations
     between the probe and the test piece are a prerequisite, since
     location information is required for the defect determination.
     Therefore, the known method is very sensitive to conventional
15   misalignments of the probe.

     Based on this, the object of the present invention is to
     further develop a method and a circuit arrangement of the known
     type in such a way that defect locations of the structure of
20   the object can be detected at high speed and with an improved
     signal/noise ratio. Furthermore, the method should be
     insensitive to possible misalignments of the probe.

     According to the invention, the method is solved, inter alia,
25   by the characterizing features of claim 1.

     It is thereby provided that a defect location is determined by
     a phase-locked addition of the stored amplitude values received
     at equal propagation times. Use is hereby made of the fact
30   that, when an object is radiated by means of a probe configured
     as a Phase Array Transducer, i.e. when emitting a complete wave
     front, echoes are received in each of the receiver elements of
     the probe switched simultaneously to receive, the amplitude
     values of the received echoes being received at the same
35   propagation times. This offers the possibility of adding the
     amplitude values of the received signals along a propagation
     time, with the advantage that the amplitude peaks identifying

5   the defect location in the structure are amplified and that the
    additional signals received by the individual receiver elements
    almost cancel one another.

    Consequently, the method according to the invention is
10 distinguished, on the one hand, by a very high speed of defect
    identification, since the sequential method common in the prior
    art is avoided due to the emission of a complete wave front
    and, on the other hand, by an improved signal/noise ratio being
    obtained in comparison to the prior art. The method is also
15 robust against e.g. a misalignment of the probe, since location
    information is not involved in the method.

    To identify defect locations on an outer surface of the object
    (outer field), in particular during the non-destructive
20 examination of pipes by means of ultrasound, point-wave signals
    which proceed from reflections at outer defects of the object
    are evaluated. An addition of the amplitude values stored in
    the storage unit does thereby not take place along one and the
    same propagation time, but in a direction which extends at a
25 right angle, or essentially at a right angle, to the
    interference patterns of the received amplitude values of the
    point-waves of the outer defects AF.

    Due to the phase-locked addition of the amplitude values along
30 a propagation time, defect locations can generally be
    identified, whereby, however, information about whether or not
    it is an outer defect or an inner defect cannot be derived from
    the sum signal. As previously stated, outer defects can be
    identified by adding amplitude values at a right angle or
35 essentially at a right angle to interference patterns of the
    point-waves emanating from the outer defect. Finally, a
    comparison of the signal detected during the phase-locked

addition of stored amplitude values along a propagation time
with the signal detected during the addition of the amplitude
values of the interference patterns takes place due to a
coincidence circuit, in which an outer defect is present when
both signals indicate a defect location.

To set a beam angle α adapted to the measuring conditions, e.g.
type of defect (longitudinal defect, inclined defect), property
of the material and the shape of the object to be examined, the
individual transmitter elements of the Phased Array Transducers
can be controlled in a time-delayed manner (phasing). When
examining e.g. a pipe, an ultrasonic irradiation can take place
in dependence on a defect location (inclined defect,
longitudinal defect), optionally in the longitudinal direction
or in the peripheral direction.

Furthermore, it is provided that, to determine the location of
the defect, a propagation time dependent amplitude correction
of the sum signal determined during the addition can be carried
out, the received sum signal being compared with a reference
value.

To further reduce the data, it is provided that the received
signals are filtered immediately after the digitalization,
preferably by means of a wavelet filter.

The object is solved by a circuit arrangement according to the
features of the characterizing part of claim 16, in which a
summer is provided for the phase-locked addition of the
amplitude values stored in the storage module.

Furthermore, the invention relates to a method for the non-
destructive examination of a contour, such as an edge, bend or

5   curvature of an object.

According to the prior art, contours of the aforementioned type
in the form of edges are examined by ultrasound with an
essentially planar wave front.   An interference pattern
10   corresponding essentially to the contour of the object to be
examined is thereby received, but the interference pattern is
unsuitable for evaluating defect locations in the structure of
the object.

15   Based on this, the object of the invention is to provide a
method for the non-destructive examination of a contour of an
object by means of ultrasonic waves which enables an improved
identification of defect points in the structure of the object
in the area of the contour.
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To achieve the object, it is proposed that the contour of a
surface of the section of the object to be examined is detected
and stored, that the independent transmitter elements are
controlled in a time-delayed manner in such a way that the
25   emanating wave front extends parallel or approximately parallel
to the surface contour and that the waves reflected by the
object are received in a time-delayed manner and produce an
essentially planar interference pattern.

30   In a preferred procedure, it is provided that the contour of
the object is identified by transmission a wave front which is
planar relative to a transmission plane to the contour to be
examined, that the waves reflected by the contour of the object
are received and digitalized by means of the plurality of
35   receiver elements that are independent of one another and the
digitalized signals are stored in the storage element at least
according to their propagation time and that the contour of the

5   object is computed from the defined distance A of the probe to
     the object and the different propagation times of the received
     signals.

     The method is distinguished by a time-delayed actuation of the
10   independent transmitter elements which transmit a wave front in
     such a way that it extends parallel or essentially parallel to
     a surface of the structure of the object to be examined.

     When the wave reflected by the contour of the object is
15   received, a time-delayed reception by means of the controllable
     receiver elements also occurs, as a result of which signals are
     received which generate an interference pattern extending
     parallel or essentially parallel to the surface of the contour
     of the object. Defect locations of the structure of the object
20   can then be easily identified in this interference pattern.

     Due to fluctuations in production, irregularities can occur in
     the contour of the object to be examined, so that, according to
     a further preferred procedure, it is provided that the contour
25   of the object is preferably identified on-line, i.e. during a
     measurement process. For this purpose, it is provided that a
     planar wave front is transmitted onto the contour to be
     examined, that the waves reflected by the contour of the object
     are received and digitalized by means of the plurality of
30   receiver elements which independent of one another and the
     digitalized signals are stored at least according to
     propagation time in a storage element and that the contour of
     the object is computed from the defined distance of the probe
     to the object and the varying propagation times of the received
35   signals.

     By the on-line resetting or adjustment to the changing contour

5   of the object, an always uniform evaluation of defect locations
       is possible.

       The readjustment is made possible by comparing the received
       interference pattern extending parallel or essentially parallel
10   to the contour of the surface of the object with a desired
       pattern, a wave front which is parallel or essentially parallel
       relative to the plane of the transmitter element being emitted
       when the received interference pattern deviates from the
       desired pattern in order to compute the actual contour of the
15   object to be examined from the reflected waves.

       Further details, advantages and features of the invention can
       be found not only in the claims, the features found therein –
       alone and/or in combination – but also in the following
20   description of a preferred embodiment that can be found in the
       drawings, in which:

       Fig. 1   shows a schematic representation of a wave front
                   emanating from a probe (Phase Array Transducer)
25   through a medium such as water onto an object to be
                   examined, e.g. a steel plate,

       Fig. 2   shows a representation of amplitude values of the
                   amplitudes received from the individual receiver
30   elements EL1-ELN of a probe with varying propagation
                   times (typical B-scan),

       Fig. 3   shows a representation of selected ray paths of the
                   ultrasonic wave front according to Fig. 1,
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       Fig. 4   shows a representation of the amplitude curve over
                   the propagation time of an individual receiver

5   planar interference pattern for the simple evaluation
           of defect locations.

           Fig. 1 shows, in a purely diagrammatic manner, an arrangement
           10 for the non-destructive examination of an object 12 which is
10   shown as a steel plate in the illustrated embodiment, by means
           of an ultrasonic wave front 16 emanating from a probe 14, the
           ultrasonic wave front being coupled into the object 12 through
           a liquid medium 18 such as water. Defect locations 20 in the
           structure of the object 12 are to be detected by the
15   examination.

           The probe 14 comprises a plurality of transmitter/receiver
           elements EL1 to ELN which are each preferably switched
           simultaneously or phase-displaced as transmitter elements and
20   preferably simultaneously as receiver elements.

           With reference to a grey-scale image, Fig. 2 shows a
           conventional B-scan of an outer defect location of a planar
           object which was taken with a Phased Array Transducer at a beam
25   angle of $\alpha = 18°$. The wave front transmitted onto the object 12
           was generated by simultaneous switching on of all transmitter
           elements.

           The individual receiver elements EL1 – ELN are plotted over the
30   horizontal axis, the signals received from the individual
           receiver elements being shown according to their propagation
           time which is plotted over a vertical axis, in succession in
           the vertical direction.

35   The intensity of the illustrated signals is defined by their
           brightness. It can be seen in the B-scan of Fig. 2 that
           different structures of the object generate different signal

5   patterns.   Thus, the surface of the object 12 generates surface
    echoes OE which are shown as diagonally extending, continuous
    lines in Fig. 2.   The defect echoes FE1 - FE12 allocated to the
    individual receiver elements EL1 - ELN are shown as horizontal
    lines.   Thus, for example, the defect echoes FE1 to FE4 of a
10 receiver element ELX and the defect echoes FE5 to FE8 or the
    defect echoes FE9 to FE 12 of additional receiver elements
    ELX1, ELX2, respectively, are shown.   In the upper left area of
    the B-scan, interference echoes IE can be identified which are
    produced due to interferences between wave fronts of the
15 individual transmitter elements of the Phase Array Transducer.

    Furthermore, the B-scan shown in Fig. 2 shows that defect
    echoes of several receiver elements, e.g. the defect echoes
    FE1, FE5 and FE3, FE6, FE9 as well as FE4, FE7 and FE10, are
20 each received at equal propagation times.   The same propagation
    times of, for example, the defect echoes FE2 and FE5 as well as
    FE3 and FE6 are to be described with reference to Fig. 3.

    The structure according to Fig. 1 is shown in Fig. 3, signal
25 paths a to i being shown purely diagrammatically.   The
    thickness of the steel plate is designated by s and the ray
    path within the object 12 by t.

    It appears that the propagation time of the defect echo FE2
30 from the sections d + 2t + e and the propagation time of the
    defect echo FE5 from the sections or propagation times e + 2t
    +d each comprise an identical propagation time. The propagation
    times of the defect echo FE3 and defect echo FE6 are also
    identical, it being noted that they are received in different
35 receiver elements.

    The signals received from a receiver element ELX can also be

5   shown in their amplitude over time.   A corresponding
    illustration (A-scan) is shown in Fig. 4. In this case, the
    individual echoes OE, FE1 to FE4 are shown as amplitude swings
    at different propagation times. According to the method of the
    invention, the amplitude values of the signals received at the
10 same propagation times, e.g. FE2 and FE5, FE3, FE6, FE9, or
    FE4, FE7 and FE10, are added along their propagation time, the
    signal shown in Fig. 5 being obtained over the time which very
    clearly represents information about the field position 20 in
    the object 12 by an amplitude increase in the range of an order
15 of magnitude.

    Since the defect echoes received from various elements ELX,
    ELX1 or ELX2 have the same propagation time, the amplitude
    values are added, so that the sum signal increases. Since the
20 noise signals contained in the A-scan of Fig. 4 cancel one
    another stochastically, the signal/noise ratio is improved.

    Fig. 6 shows a test assembly 22 for the non-destructive
    examination of a pipe wall 24 by means of probes 26, 28 which
25 are arranged along the periphery of the pipe and have curved
    surfaces 30, 32 adapted to the surface of the pipe 24, to which
    the transmitter/receiver elements EL1 to ELN, N being e.g. 128,
    of each element transmitter/receiver element EL1 – ELN can be
    switched both as a transmitter and as a receiver (sic). The
30 spatial extent of an element is adapted to the ultrasonic
    frequency f used, which is in the range of $0.2 \text{ MHz} \leq f \leq 20$
    MHz, preferably $f = 6$ MHz.

    The probes 26, 28, which are also designated as Phased Array
35 Transducers, are each connected via data lines 34, 36 with a
    first signal processing unit 38, 40 which controls the
    transmitter/receiver element EL of the probes 26, 28 and

5　　amplifies and digitalizes the received signals. The signal
processing units 38, 40 are each connected to a signal
evaluation unit 46, 48 via a data connection 42, 44, which can
e.g. be configured as FSL (Fast Serial Link). Furthermore, the
circuit arrangement comprises an interface 50 for connection to
10　　an external personal computer 52 and a microprocessor unit 54
for processing and evaluating (sorting, marking) the
information from the units 46 and 48.

Fig. 7 shows a detailed block diagram of the components of the
15　　circuit arrangement 22 according to Fig. 6. The signal
processing unit 38 comprises a pulse unit PE for controlling
the transmitter/receiver elements EL1 - EL128, which comprise
128 elements in the present example. The transmitter elements
are thereby controlled according. to a definite time pattern
20　　(phasing). The receiver elements are subsequently switched to
simultaneous reception and the received analog signals are then
conducted via a multiplexer MUX to corresponding A/D converters
AD, in the present example, to each of 32 A/D converters. The
received analog signals are digitalized by the A/D converters
25　　AD and stored in a storage element SP as a so-called A-image or
A-scan. The e.g. 32 A-scans stored in the storage element SP
according to Fig. 4 are then added during their propagation
time in a summing element SUM, according to the invention by a
phase-locked addition of the amplitude values, to form the A-
30　　scan shown in Fig. 5 in their propagation time, whereby the
advantage results that the amplitude peaks add up, as a result
of which the defect location is clearly accentuated and noise
signals mutually cancelled.

35　　Thus, the signal shown in Fig. 5 is available at the output of
the summing element SUM as an A-scan which is forwarded via an
interface I of the further signal evaluation device 46 which

5 also has an interface I. The B-scan is then forwarded to one
or more evaluation modules F1 F2 in the signal evaluation
device 46 for further signal processing. The individual
components of the circuit units 38, 46 are controlled via a
digital signal processor DSP which is connected with the
10 personal computer 52 and with the microprocessor unit 54 via a
bus coupler BK and the interface 50. The results of the signal
processing are displayed on a screen.

To obtain a data reduction prior to storing the signals applied
15 to the A/D converters AD1 - AD32, it can be provided that they
be filtered, preferably wavelet filtered, prior to storing.

The method described thus far generally serves to quickly and
effectively identify defect locations in an object. Since the
20 location information of the defect location is lost during
summation of the amplitude values along the same propagation
times, further steps are required to enable a detection of an
outer defect. For this purpose, it is proposed that the point-
wave signals reflected by an outer defect of the object when
25 examined with an ultrasonic wave be evaluated.

Fig. 8 shows strictly schematically the ray paths when the pipe
24, which has a defect location AF in an outer surface 56, is
ultrasonically irradiated. Fig. 9 shows the ray paths when the
30 pipe 24, which has a defect location IF on an inner surface 58,
is ultrasonically irradiated. The point-wave signals emanating
from the outer defect AF in Fig. 8 can also be seen in the B-
scan shown in Fig. 2, namely as defect echoes FE1 to FE4 and
their interference pattern. To identify an outer defect, a
35 "diagonal" addition can be performed, i.e. not during a
specific propagation time but at a right angle or approximately
at a right angle to the interference patterns of the received

5   amplitude values, so that an amplitude peak is produced in this
direction which contains information about an outer defect AF.

To reach a decision about whether there is an inner or outer
defect, an evaluation by a coincidence method of the sum signal
10 of the amplitude values of the same propagation times with the
sum signal of the amplitude values in direction at a right
angle or approximately at a right angle to the interference
patterns of the amplitude values received from the point-wave
signals is effected, e.g. in one of the evaluation modules F1,
15 F2, an outer defect being present if both signals show a defect
location. However, if a defect location is identified during
the phase-locked addition of the amplitude values along a
propagation time without, however, a defect location being
detected during addition of the amplitude values at a right
20 angle or approximately at a right angle to the interference
patterns, then there is an inner defect.

The following should be noted as special advantages of the
method according to the invention: the signals obtained for
25 evaluating the defect locations exhibit a better signal/noise
ratio in comparison to the prior art and can thus be evaluated
better automatically. As a result of the planar ultrasonic
irradiation of the object to be examined on the basis of the
use of a probe with Phased Array Technology, i.e. by
30 simultaneous transmission of a wave front and simultaneous
reading of the signals, a considerable time advantage is
obtained in comparison to methods with sequential technology
known from the prior art.

35 A data reduction also takes place by the phase-locked addition,
so that the subsequent signal processing is also accelerated
and simplified.

5   Fig. 10a shows a schematic representation of a probe 60 which corresponds in its structure to the probe 14 described above. A wave front 64 extending parallel or essentially parallel to a plane 62 fixed by the transmitter elements is emitted by the

10   probe 60. The wave front 64 hits an object 66 having a contour, e.g. an edge, bend or curvature, which, in the present example, has a first surface 68 which extends at an angle α relative to a second surface 70.

15   To determine the contour of the object 60 to be examined, the waves reflected by the surfaces 68, 70 are received, digitalized and stored in a storage element SP corresponding to the circuit arrangement of Fig. 7. The contour of the object 66 can then be computed on the basis of a defined distance A

20   from a reference point of the object 66 and the determined and stored propagation times of the signals. A corresponding interference pattern (B-scan) 72, which essentially corresponds to the contour of the object 66, is shown in Fig. 10b.

25   Based on the computed contour of the object 66, the transmitter elements EL1 – ELN are then controlled during the actual measuring process in a time-delayed manner in such a way that a wave front 74 emanating from the probe 60 extends parallel or essentially parallel to the contour, i.e. the surfaces 68, 70

30   of the object 60 to be examined. The waves reflected by the object 66 are also received in a time-displaced manner and from the signals thus received an interference pattern 76, shown in Fig. 11b, is generated, the wave front of the interference pattern lying in a plane.

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Defect locations can be easily identified from the data of this interference pattern.

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To enable an adaptation to a changing contour of the object, it is provided that the received interference pattern 76 be compared with a desired pattern and that, when the received interference pattern 76 deviates from the desired pattern, a
10   renewed determination of the actual contour of the object 66 takes place by e.g. a planar wave front 64 being sent onto the object 66 proceeding from the probe 60, even during a measuring process, to undertake a renewed contour measurement, on which the further measurement is then based.